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THE ENERGY COST OF ENERGY

by

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ABSTRACT

The procedure described allows various processes of energy transformation to be compared, including those using fossil fuels and solar energy and those involving conservation. The procedure permits a determination to be made about the relative feasibility and desirability of a particular process to produce a surplus of energy beyond the output that could have been created with the processing energy requirements. The analysis made under the procedure includes all the energy that is directly and indirectly committed to the process throughout the entire economy.

To quantify the feasibility of energy transformation, an input-output ratio was calculated for 44 processes. The calculations exclude fuels trnasformed directly into energy output. Adjustments were made for differences in quality, end-use, and time of use. A low ratio means that the process should receive further research and development funding or else should be dropped from consideration. The input-output ratio of a feasible transformation process may decline with time because of a resource scarcity, indicating a falling desirability. Highly desirable processes, ones with ratios that show the least signs of declining, should also be compared for future use on the basis of their relative effects on labor needs, capital requirements, the demand for critical material, and their environmental impact. Policy conclusions are hampered by an uneveness in the quality of the available data. Nevertheless, a useful and comprehensive method of energy analysis is demonstrated.

In the modern economy, we seem to employ technological strategies to capture, concentrate, and release energy in order to accomplish certain predetermined objectives. Here, these strategies are called processes of energy transformation. Through them, a flow or stock of energy is converted into a form viewed as more useful to the system of which the transformation process is a part. To carry out the transformation of an energy input into a more desirable output (e.g., coal into space heat, mechanical motion, electricity, process heat, and so on), energy flows are required with which to construct facilities and to operate and maintain the transformation processes. These flows are called processing energies.

In theory, it is possible to trace down and add up all the processing energies required from the entire economy needed for the creation and operation of a particular transformation process.[1] It is also possible theoretically to construct the most efficient alternative within existing technology to convert these processing energies into the desired output. To the extent that the transformation process under examination can produce more of the desired output than that available by using the processing energies in the least-energy-cost alternate technology, a surplus of the desired output would come into being. Society values any energy-transformation process in proportion to the amount of this

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[1] An industrial society also consumes available energy when it extracts minerals from their naturally occurring concentrations. For the U.S. economy in 1967, this quantity was less than 1.5 percent of the fossil fuel consumption [1]. Consequently, such energy forms are not included here. Two assumptions were also made: (1) that the caloric value of the fossil fuels is equal to total availability; (2) that nuclear-produced electricity and hydro-electricity can be counted as though produced by plants using fossil fuels.

physical surplus it can produce. Moreover, the value of the transforming process to society also depends on whether the ratio of the desired output to the value of the most efficient conversion process is rising, steady, or falling over the long run.

Does the transformation process produce a surplus of the desired output? And is this surplus rising or falling with time per unit of input? These questions are the focus of this paper. The first question establishes the feasibility of using a given transformation process; the second question, the desirability of its use. Together, they form a set of necessary conditions for the development of a given energy-transformation process.

This view was common among French physiocrats, such as Cantillon and Turgot, in the middle of the Eighteenth Century. Single-factor theories of value may not explain rational economic behavior today. However, when scarcity problems arise on general inputs that are critical, single-factor theories may provide useful insights. In a sense, the physically based view of value and scarcity followed here is akin to the views of Malthus and Ricardo who forecast a diminishing return from land with increasing inputs of capital and labor.

The measure proposed in this paper is similar to the empirical economic measure used by Barnett and Morse, except that they employ cost per unit of extracted resource [2]. The proposal given here is reminiscent of the surprisingly accurate physical-scarcity measure of Hubbert [3] and of the more recent theoretical measures proposed by Fisher [4].

In fact, most of the modern economists try to determine scarcity according to variations in the total extraction or discovery cost for for a unit of resource. The procedure is difficult, though, because it is hard to define the stage of resource development that is most appropriate.

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For example, Kakala [5] has shown that while lean taconite (iron) ore is more expensive than natural ore per unit of iron content, iron produced from the taconite is less expensive in the end. This overall improvement in resource efficiency stems from the fact that the taconite pellets allow a uniform and, consequently, rapid decomposition in the blast furnace. Therefore, the best approach is to clearly identify the output of an energy-transformation process and to evaluate changes in the total processing inputs per unit of output. Accordingly, the input fuel being converted by the transformation process directly into the output is not included in the present analysis. This input fuel is seen as flowing from the resource base into the economic system, and the processing energies are thought of as having already been committed to use. The processing energies are seen as originating from within the economic system and as carrying with them the option of being used in alternate devices to produce the desired output. They represent an energy "surplus" formed in a previous period and ready for "investment." The question is where should this potential energy investment go in order to achieve a maximum return.

In this paper, a method is proposed and evaluated by which the feasibility and desirability of energy-transformation processes can be determined. The degree to which a resource is exploited by a particular transformation process is tempered by its total demand for labor (particularly if it is scarce), capital and critical materials, and the environmental impact created by its use.

To avoid dollar measures of transformation processes, a physical measure is employed, in the spirit of Cantillon, Malthus, and Hubbert. The monetary value of energy may not always represent its true value to

the society because of subsidies [6], inaccurate pricing techniques and policies, and consumer confusion caused by inflation. For example, new supplies of energy seem to compete on the basis of the marginal dollar cost of energy, while energy-conservation measures tend to compete with the average cost, which generally is lower. This phenomenon occurs because utilities are facing a higher marginal cost for fuel than their customers are. Therefore, saving a unit of energy is a more stringent test of cost-effectiveness than producing a new unit. For system feasibility and desirability, the requisite criterion is one under which a process that saves a unit of energy becomes comparable to processes through which a unit is withdrawn from a stock or captured from a flow of sunlight or from geothermal flows.

Finally, since the dollar cost of energy is not yet a major factor affecting optimum production in cost-minimizing industries, optimal solutions for the minimal use of physical energy are appropriate. For example, Pilati [7] has shown that within 1 percent of the minimum dollar-cost solution for the U.S. paper industry, the physical-energy cost could vary by a factor of 2.5 for the same production level. Therefore, the criterion used here must measure energy in physical units.

This paper probably will be most useful to persons involved in economic planning. The process described may be the most appropriate one for an economy facing the scarcity of a factor that is critical in production. Attempts to estimate the future prices of an increasingly scarce resource proved to be impractical during the 1970's. The strategy proposed here may be the alternative.

DEFINITIONS AND ASSUMPTIONS

An energy-transforming system is defined as a process in which an input of a stock or flow of energy is changed into an output of greater utility to the society. "Utility" here has a physical definition: outputs of equal utility have the same thermodynamic availability and the same convenience level -- e.g., a stored or flowing energy, a solid or a liquid fuel, with or without pollution control. The system receives inputs of a raw or semiprocessed form of an energy stock or flow which it will transform directly into an output of higher utility. The system also receives inputs of processing energies from either stocks or flows of energy.

To be complete, this processing must include all the energy needed both directly and indirectly to construct, operate, and maintain the energy-transformation process. For example, the processing energy must include that needed to preprocess and deliver the fuel to the plant or facility in which the energy transformation takes place. The processing energy must include such quantities as the energy needed to mine the iron ore to provide the steel for the construction and maintenance of the transforming facility or complex.

To obtain appropriate estimates for these energy inputs requires using the results of the energy input-output model developed at the University of Illinois [8] or the equivalent. The processing units of the UI model are called primary energy -- meaning that all uses of, say, electricity have been transformed into all the energy that was removed from the ground to produce the electricity.

The processing energies do not include, however, the energy going directly from the energy sectors of the economy to final demand.

Therefore, such energy demands as the fuel for work-related travel, exports of coal, and the space heating of government office buildings are not included because of historic national accounting-base conventions. All such energy together with its processing energy amounted to 46 percent of total U.S. energy use in 1967 [8].

Costanza [9] recast the accounting procedure to include this significant amount of energy into the appropriate production processes throughout the economy. He also included an estimate of the solar energy consumed through agricultural processes. Such solar energy and labor- and government-related energy costs are not included in the calculations given here because most of the extant calculations were completed before Costanza's work was published.

Finally, the system might receive a direct input of its own output. This type of input is considered internal to processes of transformation and is reflected in a diminished net output.

The system of energy transformation is shown schematically in Figure 1.

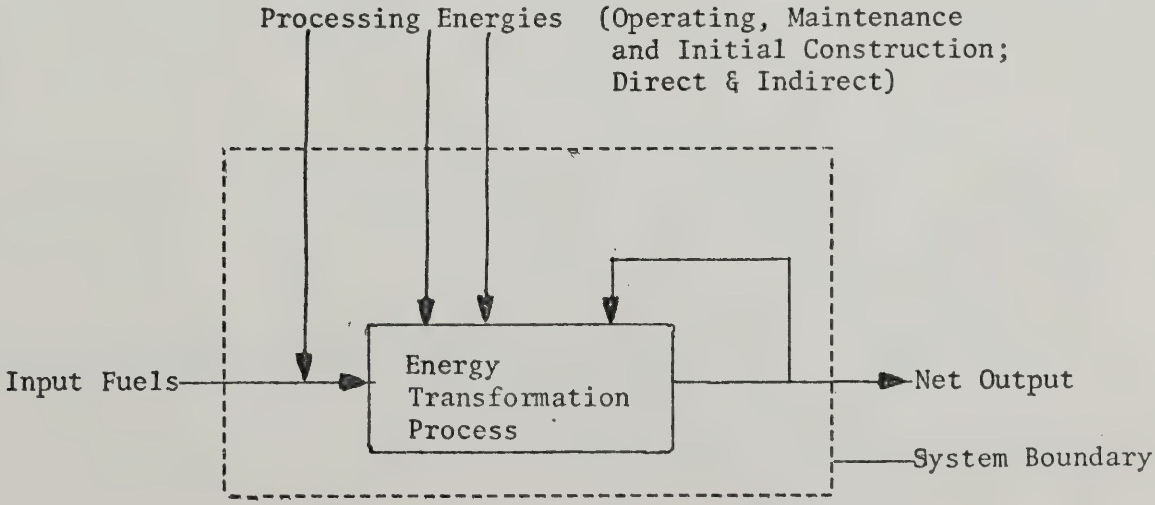
Processing Energies (Operating, Maintenance and Initial Construction; Direct & Indirect)
Input Fuels
Energy Transformation Process
Net Output
System Boundary

Figure 1. Basic energy system.

METHODOLOGY

The Return on Net Energy Investment

To describe the feasibility criterion, a term, R, is used. "R" is the return on net energy invested: the net output divided by the processing inputs. There are at least three reasonable ways to calculate the ratio. When the ratio is formed for a series of comparable energy-transformation processes, each calculation scheme gives a different ranking of the ratios. Therefore, justification must be given for the scheme selected.

One of the alternate methods is similar to the familiar return-on-investment criterion used by many corporations to rank the potential of investment projects using profits. But the view taken in this paper is that of "society-as-corporation." Therefore, the return should be based on the available surplus, or profit, which society has generated. Under this view, the output of the energy-transformation process must be divided by the processing energies required.

The second alternate method involves consideration of the direct use that a transformation process makes of its own output. This direct input (see Figure 1) could be placed in the denominator of the return ratio, or in the numerator. The latter was chosen here because to group this direct input with the processing energies would be to consider it as a surplus over which society has a choice about use. But it is not such a surplus. This direct input is a function of the transformation process used. The only requirements are that a particular transformation process be used and that its quantity be generally proportional to the output of the

process. Thus, this energy is deducted from the gross output of the process and the net output is divided by the processing energies to form a ratio called the "return on net energy investment."

For an appropriate ratio, compensations must be made in the numerator and denominator for differences in quality and types of end-use and time of use. To correct the ratio for quality and utility differences, a symbol for total energy efficiency, α, was used. Alpha represents the most efficient means existing of converting primary energy into the exact form as needed as an output. To correct for differences in the time at which processing energies are committed for use, a standard, continuous-discounting function, $e^{-\lambda t}$, was employed.

The discount rate, λ, is the mechanism by which, I believe, society implicitly expresses its desire to convert a present surplus energy into an energy-transformation process so that a greater surplus of energy can be created in the future, rather than consuming the energy now for purposes such as home heating, leisure living, and certain types of food consumption.

Because of the time element, it is far easier to express the energy uses as a time rate or as power. Figure 2 depicts the highly simplified power diagram of a general energy-transformation process.

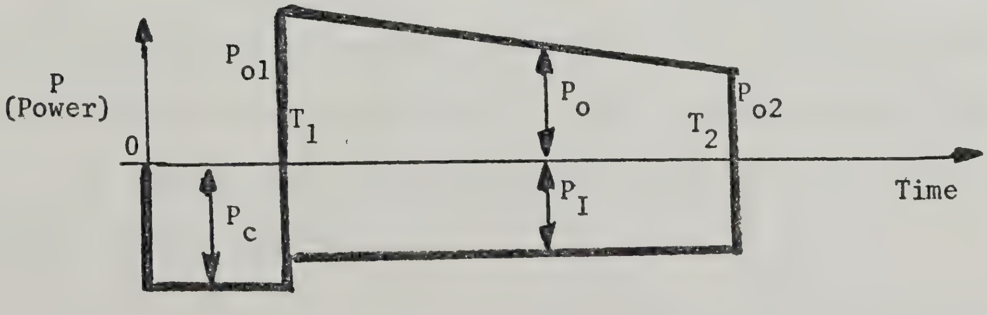

Fig. 2. Simplified power curve of a general energy-transformation process in undiscounted units.

Figure 2 displays a linearly declining output of a transformation process for constant construction, maintenance, and operating processing energies. The declining output represents an increasingly dilute fuel source, or a declining energy efficiency for an output device. An example of the latter is the tendency of photovoltaic cells to become inoperable after a time [10]. The remainder of the power curve is simplified because available data on energy-transformation processes are not detailed enough in most cases to allow a more elaborate representation.

In Figure 2, P_{o1}, P_{o2} are the initial and final net power outputs at times T_1 (the construction period) and T_2, respectively ($T = T_2 - T_1$, the lifetime); P_c, P_I represent the primary energy input rates for construction and maintenance and for operation, respectively; m is the slope of the net output rate;

$$m = \frac{P_{o2} - P_{o1}}{T_w - T_1} .$$

The term α is related to the concept of opportunity cost in economics. The difference between 1/α times the present value of the processing powers and the present value of the output power is the opportunity cost of the least-cost alternative in relation to the energy-transformation process under consideration. Through α, the concept of technological substitution is also introduced. The least-cost alternative represented by α is the best substitute process for the proposed energy transformation.

The equation for R, the return on net energy investment, based on the diagram in Figure 2 is:

$$R = \frac{\int_{T_1}^{T_2} P_o \, e^{-\lambda t} dt}{\frac{P_c}{\alpha} \int_0^{T_1} e^{-\lambda t} dt + \frac{P_I}{\alpha} \int_{T_1}^{T_w} e^{-\lambda t} dt} \; . \qquad (1)$$

Equation 1 is integrated to give

$$R = \frac{\alpha \left[(m\Delta T + \frac{m}{\lambda} + P_{o1}) e^{-\lambda \Delta T} - P_{o1} - \frac{m}{\lambda} \right]}{P_c(1 - e^{\lambda T_1}) + P_I(e^{-\lambda \Delta T} - 1)} \; . \qquad (2)$$

The normalization of the output power by the processing powers in Equations 1 and 2 is similar to the power-gain calculation used by electrical engineers for amplifying circuits. The processing powers are similar to the control power used in such circuits. The engineers are interested in how the output changes with respect to changes in the control power.

The discount rate is, of course, zero in amplifying circuits. A zero discount rate in Equation 1 produces the standard form of the net energy equation commonly used by energy analysts. Most calculations of energy feasibility [10, 11] compare the average annual net output with processing input plus the initial construction energy. The construction energy is divided by the expected lifetime of the system. In this scheme, the sequencing of the energy expenditures has no effect on the ratio of net output to net input.

The Feasibility of Energy-Transformation Processes

Energy analysis provides a more-unusual situation than is generally found in economic analyses of benefit and cost. In economics, the discount rate is known. Projects are ranked on the basis of highest to lowest R. In the case of energy discounting, one must determine first the appropriate λ and then use Equation 2 to rank the resulting values of R. To determine the appropriate λ, $R = 1$ was set in Equation 2 The equation was then applied to all existing energy-transforming processes and solved for λ in each instance.

The smallest λ is assumed to be the energy discount rate presently used by society. This minimum "revealed" λ is used in Equation 2 for all existing and proposed energy-transformation processes to produce a ranked list of R's. Under the definitions used with the theory, society would rather consume a unit of energy now than invest in a transformation process with an R of less than 1. Even though such transformation processes may have a positive R, the amount of surplus energy produced beyond the breakeven point is not large enough to justify the use of that process.

An interesting problem arises if we put the analysis on an identical basis with ordinary financial discounting. Then, the P_I of Equation 1 would be augmented by the rate at which the energy content of the fuel is processed into the output energy. With certain values of P_o, P_c, and ΔT, λ can then become complex or negative, and apparently meaningless.[2]

Another interesting problem arises that is not pursued here. Equation 2 may be used to determine the maximum R when the size or size-distribution parameters are varied. These parameters are fixed in the examples

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[2] For a positive and definite λ, $\alpha P_o > P_I \geq 0$ is the necessary condition.

used in this paper. The question is, for example, would a few, coal-fired electric plants have a higher return on energy investment than many smaller, cogenerating, coal-gas-electric ones when producing the same end-utility?

The value for α must be chosen to represent the most efficient practical way of converting from primary energy to the desired output form. The assumption made is that α applies in Equation 2 when: (1) the output energy is in the form of electricity, $\alpha = 4.0$ [8]; or (2) the output is space heating, $\alpha = 1.5$ [12]; or steam is being produced, $\alpha = 1.15$ [13]; additionally that $\alpha = 1$ in all other processes.

The last value ($\alpha = 1$ in all other processes) is tantamount to assuming that oil, coal, gas, ethanol, wood chips, and so on are of equal utility. The correction is made by calculating the best conversion efficiencies that can be achieved between the input forms and the output form. For the pruposes of this paper, the assumption that $\alpha = 1$ in all transformations producing alternate fuel forms is sufficiently accurate.

The efficiency value for electricity production ($\alpha = 4$) reflects the aggregate efficiency of all electric plants using fossil fuels in 1967. As such, the value includes oil- and gas-fired plants which did not need significant pollution-control devices. Many of the coal-fired plants already had precipitators by that time. Therefore, it is assumed here that the value of $\alpha = 4$ is sufficiently representative of the least-energy cost alternative to all of the options for producing electricity.

In converting the process inputs into the desired type of output, the efficiency $1/\alpha$ includes the energy costs of the capital needed directly and indirectly for the conversion process. This capital energy cost is

annualized and is added to the operating and maintenance energy to produce α. Although the effect of time should be considered in the α calculation, that effect is omitted here because of its small contribution to R in Equation 2. Including capital energy effects influences the energy costs of the average product produced by about 7 to 8 percent [14]. Here α includes the capital effects, but in an approximate way ($\lambda = 0$). One can arbitrarily limit the error by an iteration of the trial-and-error solution of Equation 2.

The value of α could be reduced to represent the energy lost by placing and maintaining the output in storage. Conversely, the amount of fossil fuel backup needed to provide the desired output pattern could be added to P_I. Either way, the return from the net energy investment is reduced.

The Effects of Scarcity on the Desirability of an Energy-Transformation Process

The foregoing analysis allows us to determine the feasibility of a particular transformation process at a given state of energy-resource availability. The analysis also allows us to rank those transformation processes that produce a certain desired type of output (e.g., electricity), by a descending order of feasibility.

If net energy efficiency were the only consideration, such a ranking would show the order to be followed in the development of energy-transformation facilities, that is, the relative desirability of each process. However, as each transformation process deemed thus to be feasible were to operate on the resource base, its R value eventually would decline while the facility would continue to produce a constant output.

The decline may occur because λ would be decreasing (a change in social objectives, perhaps driven by a premonition about scarcity), or because α would be decreasing (improvements made in the energetic efficiency of the least-energy-cost alternative), or perhaps because the amount of processing power per unit of output power would be increasing in a present-value sense (input scarcity). These three factors embody changes in consumer behavior, transforming technology and energy scarcity.

The processes of energy transformation with the highest, most slowly declining R values are the most desirable ones. Among these technologies, those that depend on politically stable supplies of fuels and materials and those which make socially agreeable demands on the labor force, capital market, and the environment are the ones that should be developed intensively. Transformation processes with R values that are close to or less than 1 should be dropped from consideration or be the object of further research and development.

Even so, we still do not know how to phase together the ranked technologies for energy transformation so that the net energy with the greatest present value is produced. To accomplish this phasing, assume that the only reason for the decline in R values is a scarcity of input energy, for example, the coal available to a power plant in a certain region might be found to be in thinner and deeper seams. Assume also that the peak efficiency of scale in energy production had been reached, for example, an incremental increase in the energy efficiency of a large power plant in a certain region would be exactly offset by a decline in the energy efficiency of coal-gathering and electricity transmission.

Let the cumulative present value of the output be f and the cumulative present value of the capital, operating, and maintenance processing powers (energy) be g. Both f and g are energy measures. Each transformer has a characteristic relationship, as shown in Figure 3, because of the two assumptions just made.

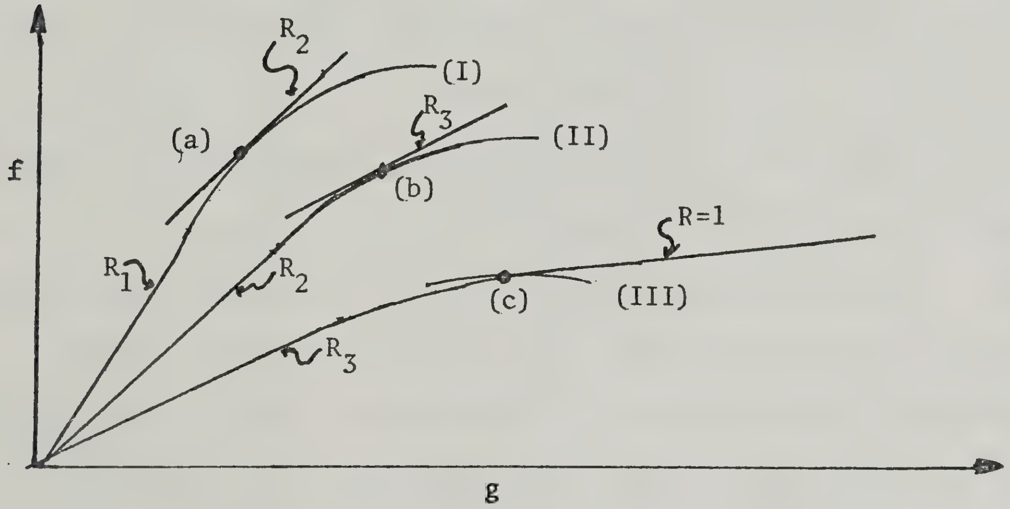

Fig. 3. The cumulative present-valued output energy, f, vs. the cumulative present-valued processing energy, g, for three energy-transforming technologies.

The three curves in Figure 3 could represent, for instance, the use of oil from Texas, the Middle-East, and Alaska to move a ton-mile of rail freight with a diesel-electric engine that burns oil. As is easily proven, the calculation for R is independent of the time lapse from f=g=0 (R depends only on time periods T_1 and ΔT). Therefore, the curves f=f(g) do not depend on the time lapse. Consequently, the curves in Figure 3 can be constructed from the present value of f and g calculated for each energy-transformation process independent of its time sequencing.

The derivative df/dg at any point along the curves for any of the three transforming technologies is the return on net energy investment, R. The process labeled I would be the logical place to begin for it has the highest initial value of R ($=R_1$) that is possible for all three processes. However, when the cumulative energy output reaches point a, it would be appropriate to switch to the second transforming technology (II). At point a, the initial R of the second transforming process would be equal to the current R ($R=R_2$) for the first process. The second process would be employed until its R value declined to point b, where it becomes equal to the highest ($R=R_3$) value for the third process. This pattern would be continued through the range of available transforming technologies until the present-valued R reached 1 (point c).

If the discounting value or the least-cost-alternative efficiency should change, Figure 3 would have to be reconstructed. The above procedure would still be followed, but using the newly computed information.

RESULTS

Data for the feasibility calculation only were found on 44 energy-transforming processes (Table 1). Only the solar-powered satellite transformation process showed a decline in output power with constant energy for maintenance and operation. This decline is not an example of the scarcity phenomena already described. Rather, it is typical of an individual satellite unit. Only if the allotted section of the geosynchronous orbit were filled with such units would scarcity begin to

Table 1.

Calculation of the Return on Net Energy Investment, R (from Equation 2).

PROCESS	YEARS		α	P_o	P_I	$P_c \cdot T_1$ (a)	$\lambda(\frac{1}{Yr})$ Percent (R=1)	R (λ=0.19)	R λ=0	COMMENT [Reference]
	T_1	ΔT								
FUEL PRODUCTION										
-Nonrenewable										
Methanol from Nat. Gas	3	20	1	1	.42	.20	76	2.1	2.3	Not used as a fuel [15]
Natural Gas	5	30	1	1	.17	1.32	28	1.7	4.7	Includes delivery [15]
Gasoline	4	25	1	1	.074	.63	48	3.9	10.1	Includes delivery [15]
-Renewable										
Intensive Tree Plantation	.5	15	1	1	.20	.091	340	4.6	4.9	Jack Pine; Chipped, Dried [17]
Natural Tree Plantation	0	15	1	1	.21	0	...	4.8	4.8	Chipped, Dried [18]
Crop Plantation (for fuel										
Corn	.5	10	1	1	.35	.013	660	2.8	2.9	New Mexico, Fert. & Dry [19]
Wheat (Dry)	.5	10	1	1	.19	.067	390	4.9	5.1	New Mexico, Fert. & Dry [19]
Wheat (Irrigate)	.5	10	1	1	.48	.043	390	2.0	2.1	New Mexico, Fert. & Dry [19]
Sorghum (Dry)	.5	10	1	1	.25	.043	455	3.8	3.9	New Mexico, Fert. & Dry [19]
Sorghum (Irrigate)	.5	10	1	1	.31	.031	500	3.2	3.2	New Mexico, Fert. & Dry [19]
Alfalfa	.5	10	1	1	.37	.051	394	2.6	2.7	New Mexico, Fert. & Dry [19]
Peanuts	.5	10	1	1	.89	.08	105	1.1	1.1	New Mexico, Fert. & Dry [19]
Methanol (Wood)	4	20	1	1	.34	1.00	32	1.6	2.6	Coal-fired distillation. Low R does not include Octane Credit [15]
Ethanol (Corn)	4	20	1	1	.75	.75	21	1.03	1.3	Low R, does not include Octane Credit [20]

(a): To put this column into average power terms, divide by T_1.

Table 1 (continued)
Calculation of the Return on Net Energy Investment, R (from Equation 2)

PROCESS	YEARS T_1	YEARS ΔT	α	P_o	P_I	P_c T_1 (a)	$\lambda(\frac{1}{Yr})$ Percent (R=1)	R (λ=0.19)	R λ=0	COMMENT (Reference)
ELECTRICITY PRODUCTION & DISTRIBUTION										
-Non-renewable										
Coal	5	25	4	1	0.09	0.48	75	16.4	36.6	U.S. Average [11] } No scrubbers
Combined Cycle (Coal)	4	25	4	1	0.03	0.84	75	14.8	62.9	[11] } No scrubbers
Eastern Surface[b] Coal										
No Scrubber	5	30	4	1	0.06	1.00	61	10.6	42.9	300 mile coal haul [21]
Limestone Scrubber[c]	5	30	4	1	0.34	1.10	57	5.8	10.6	
Western Surface[b] Coal										
No Scrubber	5	30	4	1	0.13	1.11	58	8.3	24.0	1120 mile coal haul; West. coal not as intensively scrubbed as East. coal to meet same emission standards [21].
Limestone Scrubber[c]	5	30	4	1	0.36	1.20	56	5.4	10.0	
Coal; w/Limestone Scrub.[e]	5.5	30	4	1	0.19	0.80	60	8.7	18.5	[22] Less complete analysis than [21].
Coal; Fluidized Bed (Pressurized)[e]	5.5	30	4	1	0.12	0.82	60	10.1	27.1	
Solvent Refined Coal	5	25	4	1	0.38	0.72	66	6.6	9.8	[11]
Coal-Gas	5	25	4	1	0.23	0.96	61	7.4	14.9	[11]
Shale-Gas	5	25	4	1	0.52	0.84	62	5.1	7.2	[11]
Oil-Gas	5	25	4	1	0.52	2.04	45	3.4	6.7	[11]
Natural Gas	5	25	4	1	0.32	1.08	58	6.0	11.0	[11]
Nuclear										
LWR[d]	6	25	4	1	0.14	11.27	19	1.0	6.8	[11]
HTGR[d]	6	25	4	1	0.11	18.30	13	0.6	4.8	[11]
Geothermal[e]	3.1	30	4	1	0.18	2.28	59	5.2	15.6	Liquid Dominated, High Cost Option [23]
-Renewable										
Wood (No pollution control)[e]	5	30	4	1	0.802	0.59	67	4.0	4.9	Assumed eff. = 0.3 [24]
Solar Power Satellite[e]	5	30	4	{1.00 {0.44	0.008	9.9	21	1.1	8.5	Output decline [10]
Photovoltaic } No storage or backup fuel or transmission costs	0.2	20	4	1	0	12.0	32	1.7	6.7	[25]
Wind	0.4	30	4	1	0	0.15	614	135.0	800.0	Est. Constr. Time [26]
Power Tower	5	30	1.15	1	0	0.54	49	6.7	64	Test facility; steam production only [25]

(a): To put this column into average power terms, divide by T_1.

(b): Surface mine R values only 2% higher than underground R values. A variation in the construction period T_1 of ± one year gave a variation in R of from ± 6% to ± 10%, the higher variation being associated with the higher R values.[e]

(c): A Wellman-Lord scrubbing process lowered R by 28% while the limestone scrubbers lower R by 43%.[e]

(d): If the construction period were 9 years instead of 6, the resulting λ would be 16% and 12%, respectively.

(e): The input requirements of these processes were increased by 9% to reflect the losses in transformation and transmission [27]. Data from Reference [11] contained this correction.

Table 1. (continued)
Calculation of the Return on Net Energy Investment, R (from Equation 2).

PROCESS	YEARS		α	P_o	P_I	$P_c^* \cdot T_1$ (a)	$\lambda(\frac{1}{Yr})$ Percent (R=1)	R (λ=0.19)	R λ=0	COMMENT [Reference]
	T_1	ΔT								
SPACE HEATING										
-Nonrenewable										
Gas Furnace	0.25	20	1.5	1	0.15	0.22	3.8	7.7	9.3	[28]; Operation Energy [8]
Electric:										
Nuclear LWR	6	25	1.5	1	.21	10.53	8	0.4	2.4	
Coal	6	30	1.5	1	0.307	1.00	35	2.3	4.4	Eastern Surface mine, conventional scrubber [21]
-Renewable - Solar										
Flat Plate Collector	.5 .5	20 20	1.5 1.5	1 1	0.56 0.60	5.05 6.89	17 11	0.9 0.7	1.9 1.6	Fossil fuel back up [28] Fossil fuel back up [29]
Concentrating Collector	.5	20	1.5	1	0.56	4.31	20	1.0	1.9	Fossil fuel back up [28]
Direct Solar Gain	.5	20	1.5	1	0.4	0.93	93	2.5	3.4	Fossil fuel back up [28]
CONSERVATION										
Double Pane Windows	.1	30	1	1	0	0.22	375	24.0	136.0	Chicago [30]
Ceiling Insulation (Retrofit-Nat'l. Program)	7	30	1	1	0	0.49	39	5.1	61.0	Retrofit Nat'l. Program [31]
Urban Car to Bus	1	14.8	1	1	0	0.44	118	10.2	34.0	[32]
Nat'l. Energy Plan I (Commerc. & Resid.)	5	20	1	1.0	0	0.12	76	26.4	171.0	Very approximate [33]

(a) To put this column into average power terms, divide by T_1.

lower the R values. None of the examples identified in this study showed scarcity responses.

Most of the examples were based on the University of Illinois Energy Input-Output model [8], but only one contained an indication of error tolerances [10]. However, the individual authors used different techniques to assign joint energy costs and to credit byproducts. Every possible effort was made to place the data in a common framework. Yet, these problems and the assumptions stated earlier make the results in Table 1 an interesting experiment at best.

No firm policy conclusions should be inferred without further research. For the purposes of demonstrating the potential usefulness of this approach, however, the results were analyzed as though the data were sufficiently accurate.

The examples in Table 1 were divided according to the output of the process: fuel production, electricity production, space heating, and conservation. The first three are segmented into nonrenewable and renewable sources of fuel.

Even though a certain process may have a very high return on the energy investment, the potential for that process in terms of producing significant additional quantities of useful energy may be limited. For example, in the United States, most large and convenient sites for the production of hydroelectricity are occupied; and yet, because of the negligible operating and maintenance energy, hydropower could have a very high R value. Additional units of such processes should show a rapidly declining R (calculated) as a result of increases in the capital requirements and energy-transmission losses per unit of output.

CHOOSING THE DISCOUNT RATE

Equation 2 with R value equal to 1 was applied to each process and solved for λ by trial and error.[3] The low end of the resulting λ spectrum contains both solar and nuclear processes. The lowest λ value (λ = 13 percent) is for the high-temperature, gas (nuclear) reactor (HTGR). This process, like the light-water (nuclear) reactor (λ = 19 percent) has a low value for λ because of the large capital outlay required before operation begins. Note that if electricity produced by the light-water reactor process is used for heating, the resulting λ is about 8 percent.[4]

Since it is not clear that society is aware such a practice occurs (because of the mix of plant types on the same electricity-distribution system), the higher value of λ was chosen for the light-water reactor as the base for all calculations on energy returns. If electricity were not subsidized [6] and were priced marginally rather than on an average [34], only minor amounts of electricity might be used for heat.

The flat-plate solar collectors (λ = 11 and 17 percent) and the solar-powered satellite (λ = 21 percent) have low λ values because of the large initial capital investment. The solar powered satellite also has a declining output over its lifetime because of the slow, irreversible degradation of the photovoltaic cells caused by cosmic radiation. The

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[3] Remember that none of the processes considers the energy content of the fuel which is processed into the final energy output.

[4] From Equation 2, we see that lowering α by 63 percent (4 to 1.5) drops the R value by 63 percent.

discounting process makes this decline less important than it would be if λ were zero.

The solar-concentrating collector (λ = 20 percent) provides only a small improvement over the flat-plate collector. Ethanol from corn (λ = 21 percent) owes its low λ value to the high operational energy generally employed to fertilize the corn and to distill the alcohol.[5] Methanol from wood (λ = 32 percent) is a superior process to ethanol (corn) in overall energy efficiency and has the same λ as earth-based photovoltaic cells. Natural-gas production (λ = 28 percent) is a nonrenewable energy source with a surprisingly low λ value. The relatively high λ values for photovoltaics, windmills, and the solar power-tower would be reduced considerably if energy costs for storage were included.

Therefore, the only appropriate solution to Equation 2 with R = 1 was for the light-water nuclear reactor. This is the only technology with a low λ value that is presently used to transform significant quantities of primary energy into desired forms of output (electricity). The discount rate for this technology (λ = 0.19) represents the lowest that society will accept, assuming that such a rate even exists. No other widely used technology has a lower λ value.

How sensitive is this rate to changes in the key variables? We can define a standard elasticity equation as:

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[5] Suppose that the distillation process involved in making ethanol from corn had been solar-heated. How would this energy been included in Equation 2? First, the heat energy absorbed would have been included in the operating energy. Second, the α would have to be modified to contain the efficiency of the conversion of that solar radiation absorbed to a similar form of output (possibly dried biomass).

$$e_{T_1\lambda} = \frac{T_1}{\lambda} \frac{\partial\lambda}{\partial T_1}, \qquad (3)$$

which is the elasticity of λ with respect to T_1. A small change in T_1 will produce an $e_{T_1\lambda}$ change in λ.

Equation 3 was applied to each of the variables. The results are given in Table 2.

Table 2

Elasticities for the Key Variables in Equation 2 (R = 1)

Applied to the Light-Water Nuclear Reactor Process ($\lambda = 0.19$)

T_1	ΔT	P_o	P_I	P_c
-0.995	-0.001	+0.960	-0.960	-0.431

For example, an increase of 1 percent in T_1, the construction period, would reduce λ by 0.995 percent. A 1-percent increase in the energy rate used in the construction period, P_c, would reduce λ by 0.431 percent. The lifetime, ΔT, is not an important variable in solving for λ; but T_1, P_o, and P_I are important.

The values in Table 2 reveal the sensitivity of λ to small changes. For a large change, Equation 2 (R =1) must be solved again for λ by trial and error. When this was done, the λ sensitivity was not great. For example, a change of 10 percent in each variable produced a maximum change in λ of 2.5 percent. It is safe to conclude that λ is not very sensitive in the variables T_1, ΔT, α, P_o, P_I, or P_c; also, that T_1 is the most important variable with regard to the determination of λ.

The construction period, T_1, is the least accurate of the variables in Table 1. T_1 is derived from pure guesswork in some instances, to averages of actual practice recently. In every case, the construction period is that time during which $P_c T_1$ is expended.

Another assumption is that indirect capitalization takes place during T_1. Here is a key problem in this kind of analysis. The time and energy spent on the direct and indirect capitalization must be assigned to the joint products on what amounts to an arbitrary basis. The longest of these assigned periods is T_1. The shorter periods are superimposed in the most practical possible order. This procedure may not represent reality since iron must be made before steel, which is needed for sheet steel. That, in turn, is necessary for power-plant fabrication, and so forth. The practical time for these processes may actually exceed T_1. However, the construction period encompasses the bulk of the capital-forming time for any given process of energy transformation and is, therefore, sufficiently accurate for the purposes here.

Finally, we must realize that the λ discussed in this paper is thought of as an aggregate value for the whole society. Regional variations in the discount rate are entirely possible. These variations might arise from differing local views about the certainty of future fuel supplies and their future costs. The concepts set forth in this paper are so tenative that delving into regional differences in discount rates must wait for appropriate opportunities with suitable data.

THE ENERGY RETURN ON NET ENERGY INVESTMENT

When we compare the R values, what do we find? The liquified fossil fuels appear to be superior to the liquified fuels made from vegetables. Among the renewable fuels, trees are better than field crops such as corn, whether one is making a solid or a liquid fuel. This is probably because a young to medium-aged forest can convert more solar radiation into storage per year and per acre than a cash crop can.

Irrigated crops have lower R values than the same crop without irrigation. Here we see the tradeoff between the fossil fuels (irrigation) and land (yield). Finally, on the basis of 1 data point (peanuts), it would seem that the grass crops (corn, wheat, sorghum) are better than legumes. The production and distribution of natural gas has a surprisingly low R value because of the extensive investment required in pipelines and the high energy costs associated with pumping operations.

In the production of electricity, fuels and geothermal sources appear to be superior to nuclear and solar-based processes. The possible exceptions are windmills (no storage costs included) and wood. Coal-fired power plants without environmental-protection equipment are the most feasible processes (e.g., the average conventional coal-electric and combined-cycle processes).

In a more detailed view, we compared coal-electric processes in the Eastern and Western United States, with and without appropriate scrubbers. Scrubbers reduce the effectiveness of coal-electric plants from 50 to 75 percent. This efficiency reduction is one way to assess the energy cost of air-pollution abatement. With scrubbers, Eastern coal is slightly more energy-effective than Western coal. The energy return is not affected by the type of mine.

The pressurized fluidized bed coal-electric process,[6] prescribed because of its low levels of harmful effluent, has an R value that is 16 percent higher than that of a scrubbed Eastern coal-electric plant. To control coal-associated air pollution, the solvent-refined coal and coal-gas processes are approximately as feasible as using either the scrubbers or the fluidized-bed processes. The shale-gas-electric process is better than the (heavy) oil-gas-electric process.

The natural gas-electric process, normally thought of as attractive because pollution control is achieved without a major investment, has a similar energy return to the scrubbed-coal electric or the fluidized-bed coal processes under the analysis presented here. The geothermal-electric process, which is free of air pollution, is classed as nonrenewable because the resource rock is actually mined of its heat content. This process has a high R value, comparable to the coal-gas-electric process and the solvent refined and scrubbed-coal processes.

Of the renewable electric processes, the photovoltaic, wind, and power-tower do not store energy. Consequently, they cannot be compared to the other process in Table 1. The wind machine is a superior energy-converter compared to the photocell or the concentrated solar-heated boiler (power-tower). The wood-electric and the solar satellite are comparable processes because, theoretically, the electric energy is available on demand from either process. The wood-based process appears to be superior, although reliable data for either process are not available.

The last comparison points up one of the most important technological questions of our time, Can man devise a renewable energy source to meet

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[6] This process and its companion in Table 1 were not analyzed in as much detail as the others [10, 11, 23]. They appear only to give the relative energy efficiencies.

an arbitrary demand cycle that is superior in energy efficiency to the natural processes of capturing, storing, and releasing high-quality energy? The data in Table 2 indicate that we have not yet managed to duplicate the efficiencies of natural energy. However, the wood-electric process does not include pollution-control effects and is, therefore, not strictly comparable to a solar satellite as an energy source.

None of the solar space-heating options compare well with the gas-furnace heating system. The direct-gain, or passive solar space-heating, process works with flat-plate, or concentrating, solar collectors and is approximately equivalent to the scrubbed-electric heating process. All of the space-heating processes investigated had a greater net energy return than the light-water nuclear reactor.

Note that in this paper, the solar processes use gas heaters to provide heat when solar radiation is not available. By this procedure, one of the energy costs of convenience (demands for energy that differ from the natural solar cycle) can be estimated.

The conservation projects appear to be feasible in terms of overall energy efficiency. They compare well with fossil-based processes in which pollution-control strategies are used. The conservation processes are somewhat difficult to fit into the simplified graph in Figure 1 because they are national programs with effects that are being felt before the construction programs are finished. This was true of the ceiling-insulation program and of National Energy Plan I.

The phenomenon of the extended process points up an interesting and complex problem. Both conservation and supply-construction programs can theoretically proceed at rates that will not produce a net energy output.

In general, the data in Table 1 are achieved only when building rates slow toward a replacement level. Clearly, a proper energy analysis would be applied to the entire program from initiation until a steady-state condition is reached -- with the energy costs and benefits being placed in present-value terms.

Also note the effect on R values of different λ values. When $\lambda = 0$, for example, Equation 1 reduces to the form commonly used by energy analysts. The ranking of the R values in Table 1 is changed substantially when $\lambda = 0$, mainly because some processes have long construction periods with heavy capital commitments in relation to others. If the λ value and the real financial discount rate are equal, then financial feasibility necessarily means energetic feasibility, providing that the economy can be thought of as having a single energy source [35]. However, the physical discount rate now appears to be several times higher than the real financial rate, so we can imply nothing about physical feasibility from financial feasibility. Eventually, it seems possible that the two rates may converge as the stocks of energy resources are reduced.

If the λ value does represent the society's time value of energy, then it should rise during periods when energy is perceived as being plentiful and should decline during periods of energy scarcity. From the values in Table 1, we find that a society which burns wood has a value for λ of 67; in a coal-burning society, λ ranges from 75 down to 55 with pollution control; and in the nuclear age, we have a λ value of 19. The minimum λ seems to have generally declined in the United States over the past 100 to 125 years. From the consumer's viewpoint, this phenomena would indicate a gradually increasing scarcity of available energy. Eventually, as fossil and nuclear fuels are depleted, the minimum λ will decline until

it reaches the level for the steady-state, agrarian society, probably zero. No surplus energy would be needed to replace the depreciating structure and provide for all aspects of the renewal cycle of society and family life. These needs would be considered part of the maintenance energy demand.

Also recall the classic argument of Page [36], who said that owing to the unavoidable decline in the availability of resources because of use by the present generation, the only way in which we could be totally fair to future generations is to leave them the tools and the knowledge to derive as much benefit as we could have done originally using the known resources that remain. To accomplish this goal, no better procedure than the one given here seems to be conceivable.

SUMMARY

The present value, net energy feasibility of 44 energy-transforming processes was calculated and compared on a purely energy-efficient basis. The method allows a quantitative comparison of all forms of supply and end-use processes -- whether they are from renewable or nonrenewable sources of energy, whether they are fuel, electricity, space heating or transport end-use, or whether the energy gain results from a substitution that frees energy for use elsewhere. Processes using fossil fuels generally are superior to most of the solar and nuclear ones. With certain noted exceptions, the conservation processes studied are comparable to fossil-fuel processes.

The data are of limited validity, not allowing any firm policy conclusions to be suggested. Even so, a useful method of energy analysis, I believe, has been created and demonstrated. The availability of suitable data with the requisite validity would permit the analytical procedure to be applied broadly in the process of formulating and implementing energy policy.

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